EXTENDED ABSTRACT:

Energetic ^{3}He in the Interplanetary Medium and its Acceleration by Shocks

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Abstract. Observations of a number of relatively large solar energetic particle (SEP) events that have occurred since the launch of ACE in August 1997 have shown that the ratio of ^{3}He/^{4}He can be enhanced over the solar wind value ($\sim 4 \times 10^{-4}$) by more than an order magnitude in such events. Since particle acceleration in these "gradual" SEP events is thought to be caused by CME-driven shocks traveling through the solar corona and interplanetary medium, a source of ^{3}He in addition to the solar wind appears required to provide the seed material. One possible source recently suggested by Mason et al. (1999) is the accumulation of supra-thermal ions from preceding impulsive SEP events, which individually may be too small to be detected with present instrumentation. Using data from the Solar Isotope Spectrometer on ACE we present additional evidence for ^{3}He enhancements at MeV energies in gradual events. In addition, by using data from days with the lowest He intensities we derive "quiet time" energy spectra of ^{3}He. These spectra turn up at low energies suggesting a solar origin consistent with the Mason et al. proposal.

INTRODUCTION

Particle acceleration in solar energetic particle (SEP) events is thought to be caused by two distinct mechanisms (1). First, the energy released by magnetic reconnection can cause acceleration at the site of a flare on the Sun, although the details of the mechanism remain uncertain. Second, the passage of coronal mass ejections (CMEs) thorough the corona and interplanetary space can drive a shock which will accelerate particles from the medium it is traversing.

Extensive efforts have been made to establish sets of observable characteristics of SEP events that can be used to distinguish which acceleration mechanism was operative in a particular event (2). Events classified as "impulsive" or "gradual" (based on the duration of the x-ray emission) are thought to be associated with acceleration by flares and CME-driven shocks, respectively. It is generally found that the SEP events with the highest particle intensities near Earth are of the gradual type.

Compositional signatures have also been extensively studied. In gradual events, heavy element abundances are generally consistent with coronal (or solar wind) values, with relatively modest fractionation which can be correlated with the mass-to-charge ratio (M/Q) of the ions (3). In impulsive events, more extreme deviations from coronal abundances are observed. Most notably the ^{3}He/^{4}He isotope ratio can exceed the solar wind value of $\sim 4 \times 10^{-4}$ (4) by as much as four orders of magnitude, and heavy elements exhibit a pattern of generally increasing enhancements with increasing atomic number, Z, with Fe/O reaching values $\sim 10\times$ the coronal value of 0.13 inferred from gradual SEP events (1). The extreme enhancements of ^{3}He are thought to result from selective heating by some resonant process acting on the preflare material. The degree of correlation between ^{3}He and heavy ion enhancements and the conditions under which such correlations occur are an active subject of debate and require further clarification.

In the prevailing view of the origin of SEP events one would expect very small values of the ^{3}He/^{4}He ratio in large, gradual events. Prior to the launch of the Advanced Composition Explorer (ACE) there were reports of a few large events with appreciable enhancements of this ratio and it had been suggested that such events could be of a "mixed" character containing both shock-accelerated material and flare-associated particles (see (2) and references therein). However, earlier instruments lacked the combination of sensitivity and resolution needed to detect ^{3}He in gradual events at levels much below $\sim$ 10% of ^{4}He under normal conditions.

Isotope spectrometers on ACE are able to resolve ^{3}He at least down to levels of a few tenths of a percent of ^{4}He. At energies < 1 MeV/nuc, data from the Ultra-Low Energy Isotope Spectrometer (ULEIS) have shown the presence of significant ^{3}He enhancements in several gradual events (5, 6). At higher energies, $\gtrsim$9 MeV/nuc, observations with the Solar Isotope Spectrometer (SIS) indicate ^{3}He/^{4}He ratios exceeding $\sim$ 0.4% in at least half of the 11 large SEP events that occurred between November 1997 and June 1999 (7, 8).

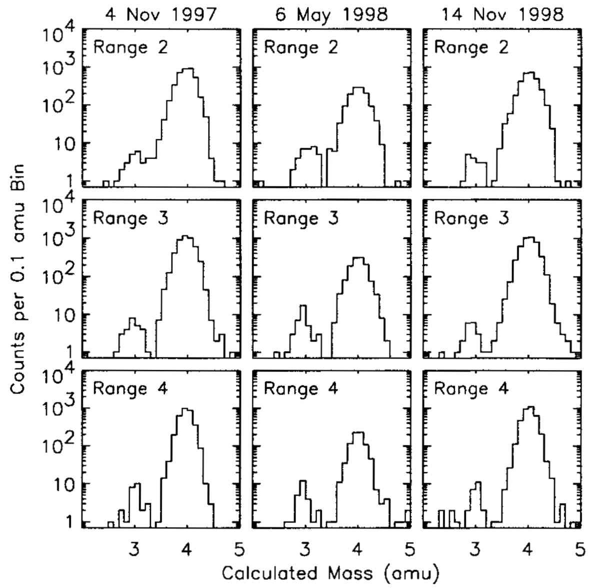

FIGURE 1. He mass histograms for SIS ranges 2 through 4 from three large SEP events. Energy intervals (MeV/nuc) for ^{4}He and ^{3}He in SIS are: Range 2, 6.5–7.6 and 7.7–9.0; Range 3, 7.7–10.1 and 9.1–11.9; Range 4, 10.2–13.8 and 12.0–16.3.

SIS OBSERVATIONS OF SEP ^{3}He

The SIS instrument (9) identifies the charge and mass of energetic nuclei using measurements of dE/dx, total energy, and trajectory in stacks of silicon solid-state detectors. For the present study where it is necessary to identify small fluxes of ^{3}He in the presence of significantly larger ^{4}He intensities, we consider particles which stop in the fourth, fifth, or sixth detectors in the stack (called ranges 2, 3, and 4). For each of these nuclei there are between 3 and 5 mass measurements which are required to be consistent to reduce backgrounds. Figure 1 shows He mass histograms for these three ranges from three of the large SEP events that have been studied (4 Nov 1997, 6 May 1998, and 14 Nov 1998). In each of these histograms there is a clearly resolved ^{3}He peak. In some of the other large events the SIS data do not show a distinct ^{3}He peak, but sensitivity is sometimes limited either by low statistics or residual spill-over from ^{4}He.

Figure 2 contains plots of ^{3}He and ^{4}He particle intensities vs. time for the same cases shown in the histograms of Figure 1. Of particular interest is the comparison of the time dependences of the two different isotope intensities. In the 4 Nov 1997 event, the ^{3}He intensity is relatively constant throughout the $\sim$ 2 days of the event, even as the ^{4}He intensity is declining. The duration of enhanced ^{3}He intensity is much longer than the fraction of a day typical of impulsive events. The extended duration is compatible with acceleration by the propagating shock in a gradual event, and such a shock was observed passing Earth in this event. However, the different time profiles of the two He isotopes suggests different spatial distributions of the ^{3}He and ^{4}He being accelerated by the shock. Alternatively, the ^{3}He might result from a series of unresolved impulsive injections from ab active region on the Sun.

In the 6 May 1998 event, the ^{3}He intensity also does not decline as rapidly as the ^{4}He in the late stages. More striking, however, is the strong ^{3}He "spike" in the first hour or two of the event. There is a corresponding brief, early component of ^{4}He, but this ^{4}He spike is partially masked by the higher gradual ^{4}He component. A similar spike is also present for the heavy element fluxes in this event (10). The presence of this initial spike lasting less than 0.1 day and having a ^{3}He/^{4}He ratio approaching 10% (significantly greater than in the period immediately following) is suggestive of a "mixed" event. The spike may contain material impulsively accelerated in a flare while the more gradual intensity variation over the following day may be caused by continuing shock acceleration from the interplanetary medium. As in the 4 Nov 1997 event, there is a clear enhancement of ^{3}He/^{4}He in this gradual phase as well.

In the 14 Nov 1998 event, the ^{3}He intensity tracks that of ^{4}He more closely than in the two events discussed above, but at least in range 2 there are indications that the ^{3}He intensity may not be tracking the decline of the ^{4}He intensity.

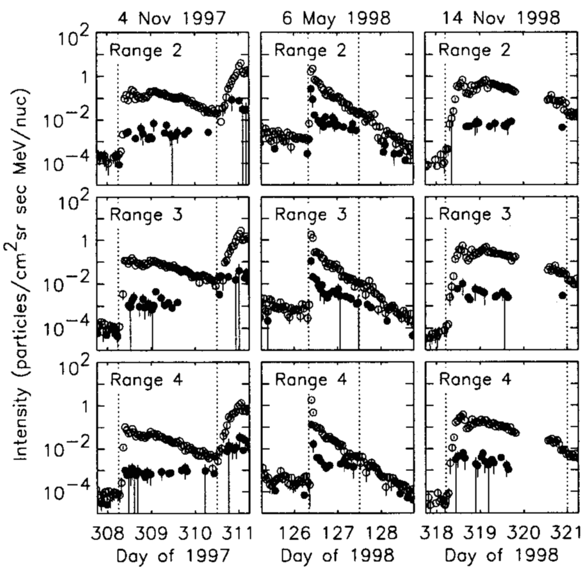

FIGURE 2. Time–intensity plots for He isotopes in SIS ranges 2 through 4 from three large SEP events. Points show 1 hr average intensities of ^{4}He (open circles) and ^{3}He (filled circles). Dotted lines indicate start and stop times used for accumulating histograms in Fig. 1. Energy ranges are given in the caption to Fig. 1. A data gap occurred during the decline phase of the 14 Nov 1998 event.

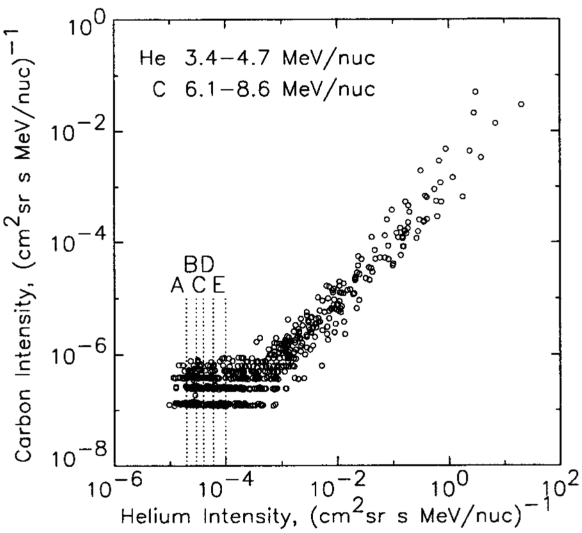

FIGURE 3. Correlation of daily averages of low-energy He and C rates measured in SIS range 0. Vertical dotted lines indicate the He intensities used as boundaries of quiet time levels A through E.

QUIET-TIME ^{3}He

Even at the relatively high energies to which SIS is sensitive ($\gtrsim$4.5 MeV/nuc for ^{3}He), more than 50 ^{3}He-rich SEP injections have been identified from the first 24 months of ACE operations. While these impulsive events could serve as sources of energetic ^{3}He that could be further accelerated by interplanetary shocks in subsequent gradual events, the short duration over which the individual ^{3}He enhancements persist near Earth suggests that this process could only occasionally account for ^{3}He excesses in gradual events. Since such excesses appear to be present in a significant fraction of the events observed by SIS, an additional source of ^{3}He appears to be required.

There are numerous "quiet" days during which no more than a few He nuclei are observed in the lowest SIS energy interval (range 0). Mason et al. (6) have suggested that even during such quiet periods there may be enhancements of ^{3}He caused by numerous small impulsive events with intensities too low to be individually distinguished at the sensitivity level of the instrument. Following this suggestion we have investigated the energy spectra of the He isotopes integrated over a large number of quiet days.

SIS daily average fluxes of range 0 He (3.4–4.7 MeV/nuc) and C (6.1–8.6 MeV/nuc) were used to select quiet days. As shown in Figure 3, the He and C fluxes are generally well correlated. However, when the He intensity is $\lesssim 10^{-4}$ (cm^{2}sr s MeV/nuc)$^{-1}$ (which we henceforth adopt as a quantitative definition of "quiet") the C count rate is no more than a few per day and does not provide a very useful measure of how quiet the period is. Using the He rate one can make finer distinctions among these quiet days, but since the quiet time He at solar minimum is dominated by anomalous cosmic rays (ACRs) these differences may not provide much information about how low solar particle activity actually is. Nevertheless we have divided the quiet times into 5 distinct levels (designated A through E) as indicated by the dotted lines in Figure 3. Figure 4 shows the time distribution of the quiet days at these different He intensity levels. The concentration of the quietest (A level) days toward the later part of the study interval reflects the decline of the ACR ^{4}He intensity due to the increase of solar modulation associated with the onset of solar cycle 23.

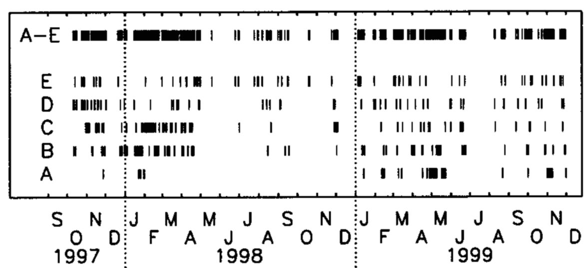

FIGURE 4. Time periods included in "quiet time" data sets. Levels A through E correspond to the following range 0 He intensity intervals in units of 10^{-5} (cm^{2}sr s MeV/nuc)$^{-1}$: < 2, 2–3, 3–4, 4–6, and 6–10.

Figure 5 shows He mass histograms from SIS ranges 1 through 4 summed over all of the quiet days and over the quietest subset of these days. Each of the histograms contains a well-resolved ^{3}He peak. Figure 6 shows the energy spectra of ^{3}He and ^{4}He derived from these data. The ^{3}He intensities are typically several percent of the ^{4}He values during these quiet periods. However, since the ^{4}He should be due primarily to ACRs and any ACR ^{3}He should be at a much lower intensity level than the ^{3}He SIS is measuring, one should expect the ^{3}He/^{4}He to vary as the solar modulation level changes.

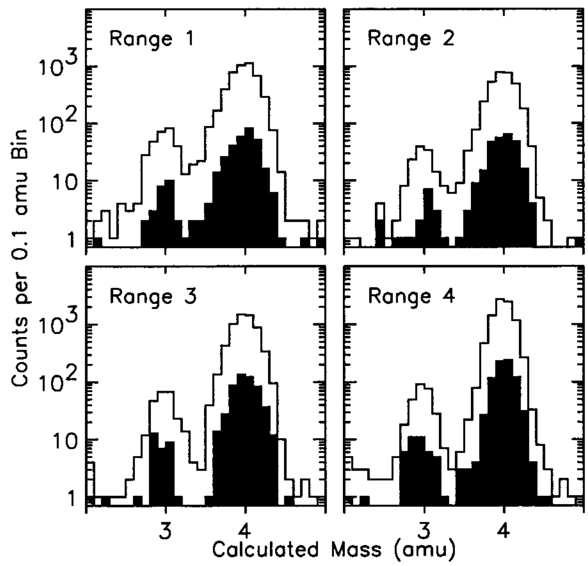

FIGURE 5. Quiet-time He mass histograms for 4 SIS ranges. Filled histograms are for days with He intensity $< 2 \times 10^{-5}$ (cm^{2}sr s MeV/nuc)$^{-1}$ (A level) and unfilled histograms are for days with He intensity $< 10^{-4}$ (cm^{2}sr s MeV/nuc)$^{-1}$ (A–E levels combined). Range 1 includes 5.0–6.3 MeV/nuc ^{4}He and 6.0–7.5 MeV/nuc ^{3}He. The other energy intervals are given in the caption to Fig. 1.

Some of the interplanetary ^{3}He is known to come from galactic cosmic rays (GCRs) where this isotope is produced by nuclear fragmentation of heavier species, primarily ^{4}He. While solar modulation prevents cosmic rays with interstellar energies less than a few hundred MeV/nuc from penetrating into the inner heliosphere, adiabatic deceleration of higher energy cosmic rays produces a low-energy tail with a characteristic "$J = AT$" form (intensity proportional to kinetic energy) at the energies we are considering. The straight line in Figure 6 shows a fit to the low-energy solar-minimum ^{3}He spectrum measured by Voyager in 1977 before leaving the inner heliosphere (11). The highest-energy SIS fluxes shown are consistent with the extrapolation of the Voyager spectrum (dotted line). However, at lower energies the SIS data show a turn-up rather than the power-law fall-off expected for the galactic background.

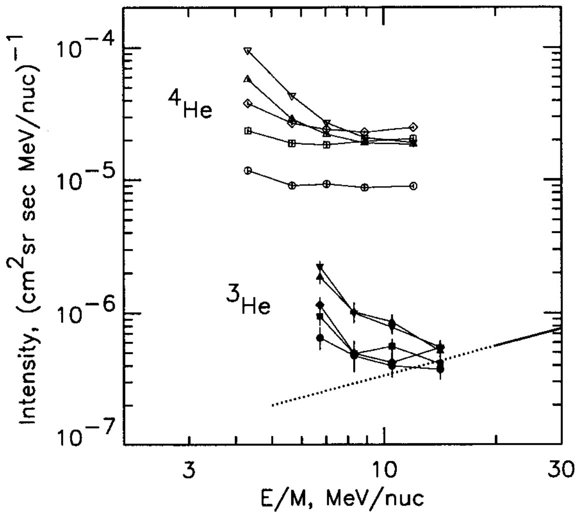

FIGURE 6. Quiet-time energy spectra for He isotopes measured with SIS. Different spectra correspond to different levels of total range 0 He intensity (A–circles, B–squares, C–diamonds, D–up triangles, E–down triangles) as indicated in Fig. 3. The line indicates the 1977 solar minimum ^{3}He spectrum (solid) reported by (11) and its extrapolation to lower energies (dotted). The ^{4}He spectra should have significant contributions from ACRs.

DISCUSSION

The low-energy turn-up of the measured quiet-time ^{3}He energy spectra suggests solar or interplanetary acceleration of these particles. Furthermore, the observed quiet-time ratio of several percent for ^{3}He/^{4}He at the lowest SIS energies (after correction for a modulated galactic contribution) sets a lower-limit on the ^{3}He/^{4}He ratio in the source from which this material is derived. The actual ^{3}He/^{4}He ratio could be significantly greater since the observed ^{4}He is dominated by ACRs. The combination of an energy spectrum that turns up toward low energies and a high ratio of ^{3}He/^{4}He appears to be consistent with the suggestion (6) that many small, ^{3}He-rich events are providing supra-thermal seed material which can be accelerated by interplanetary shocks to provide the sizeable abundances of ^{3}He observed in a significant fraction of large, gradual events.

To further test this model it would be of interest to examine quiet-time spectra of the He isotopes over a broad range of energies by combining data from ULEIS, SIS, and the ACE Cosmic Ray Isotope Spectrometer (CRIS). Such spectra extending from tens of keV/nuc to over 100 MeV/nuc will include contributions from GCRs, ACRs, and probably SEPs. These separate components should have different time dependences as the activity level increases in solar cycle 23: the SEP intensity should increase, the GCR intensity should decrease gradually, and the ACR intensity should decrease more rapidly. By observing the time evolution of the overall spectrum it may be possible to establish whether sub-threshold impulsive events are the source of the ^{3}He observed in gradual events. In addition, it will be of interest to extend studies (6, 12) aimed at determining whether small, impulsive events are contributing significantly to the low-energy fluxes of heavy elements during quiet times and establishing the extent to which this material is contributing to the heavy element abundances observed in gradual events.

ACKNOWLEDGMENT

This research was supported by the National Aeronautics and Space Administration at the California Institute of Technology (under grant NAG5-6912), the Jet Propulsion Laboratory, and the Goddard Space Flight Center.

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